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DELETE ANALYSIS OF PARKING LOTS?

SUMMARIZE DISCUSSION OF BARRIERS?

EVALUATING THE LIFECYCLE COSTS OF REFLECTIVE PAVEMENTS

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ABSTRACT

Lightening the color of street pavements in cities is a promising approach to reducing the urban heat island effect. LBNL conducted the first comprehensive assessment of the lifecycle costs and market barriers related to the use of light-colored or “reflective” pavements as alternatives to conventional asphalt concrete and found that full-depth portland cement concrete (PCC) can be a cost-effective alternative when considering streets that need to be reconstructed. Similarly, thin overlays of PCC, or “ultra-thin whitetopping”, were found to be cost-effective when repairing arterial streets and intersections. Light-colored chip seals and other chipping methods exhibit the potential to be cost-effective alternatives to conventional surface maintenance techniques, but their incremental costs are as of yet uncertain. When evaluated in the context of Los Angeles, the range of incremental costs that would allow these light-colored chipping methods to be cost-effective ranged from less than $1 to more than $11 per square yard. Although market barriers exist for all the reflective pavement types considered in the study, a number of cost-effective alternatives are available for nearly every urban pavement application, and this study provides guidance to policy makers for identifying and overcoming those barriers.

I. INTRODUCTION

During the summer months, many cities experience the "urban heat island" effect – an increase in air temperature 6-8ºF beyond that of the surrounding rural areas. Heat islands are caused by the absence or reduced frequency of vegetation, especially trees, which normally serve to cool the air via shading and evapotranspiration, and by the presence of dark-colored surfaces, particularly roofs and pavements, which absorb sunlight and reradiate solar energy as heat [1]. Heat islands are an air quality concern because they increase the frequency of smog episodes and the intensity of smog formation, a temperature-dependent photochemical reaction. Heat islands are also an energy efficiency concern because increased air temperatures raise air-conditioning loads in buildings, in turn raising energy consumption, peak energy demand, and energy prices.

Although, research and support for light-colored or "reflective" pavements as a way to reduce the heat island effect is just beginning in earnest, pavement reflectance and surface temperature are not new subjects to the scientific community. Lighting engineers have long considered pavement reflectance in the design of roadway lighting systems in Europe [2]. In 1983, the American National Standards Institute (ANSI) recognized the contribution of pavement reflectance to the performance of roadway lighting systems in its publication *American Standard Practice for Roadway Lighting* [3]. More recently, pavement engineers have examined the relationship between pavement surface temperature and air temperature. Solaimanian and Kennedy [4] and Dempsey *et al.* [5] measured and modeled both diurnal- and peak-temperature differences between air and pavement and predict that, during the summer months, pavements can get up to 40ºF hotter than the surrounding air. The relationship between pavement reflectance and surface temperature has also been studied quantitatively [4, 6] demonstrating that increasing pavement reflectance can indeed lower pavement surface temperatures significantly.

The objective of this study is to bring the existing body of scientific knowledge into the context of today's pavement market in order to evaluate what cost-effective opportunities may currently and potentially exist for reflective pavements. Specifically, we wish to evaluate the lifecycle costs and market barriers associated with using reflective paving materials in urban environments as a measure to mitigate the heat island effect.

Since heat islands are necessarily an urban phenomenon, reflective pavements for the purpose of heat island mitigation are necessarily urban pavements – streets, parking lots, sidewalks, and private surfaces like driveways, patios, and walkways. Recent studies have shown that among the different types of urban pavements, streets and parking lots account for the majority of paved surfaces in cities [7]. Thus, we have chosen to focus this study on street and parking lot pavements.

In this study, we calculate and compare the lifecycle costs of conventional asphalt concrete (AC) pavements to pavements with higher reflectivity. We consider five existing reflective pavement technologies – portland cement concrete (PCC), porous pavements, resin pavements, light-colored chip seals, and light-colored asphalt emulsion sealcoats – and two proposed approaches that would increase the reflectivity of asphalt concrete. We then briefly examine the market actors and driving forces associated with urban pavements, and outline the existing market barriers faced by reflective pavement technologies.

II. DETERMINING THE LIFECYCLE COSTS OF REFLECTIVE PAVEMENTS

METHODOLOGY OF PAVEMENT LIFECYCLE COST ANALYSIS

We chose to follow the latest pavement lifecycle cost analysis (LCCA) methodology recommended by the Federal Highway Administration (FHWA), modified to allow us to make comprehensive observations about the lifecycle costs of reflective and conventional pavement designs over a wide range of scenarios. As an investment decision-making tool, the boundaries of pavement LCCA are drawn at the project-level such that all the pavement designs considered provide the same level of performance. In this study, we wish to compare the lifecycle costs of AC to those of alternative pavement designs that provide not only equivalent performance but also increased reflectivity at the pavement surface. Additionally, we wish to make observations about how pavement lifecycle costs vary over a wide range of controlling parameters such as functional class (e.g., arterial streets vs. residential streets) and maintenance policy. In this way, we draw two sets of boundaries in this study – the first being at the project-level in order to compare specific conventional and reflective pavement designs, and the second being at the pavement network-level in order to evaluate how the lifecycle costs of pavements vary in different situations. We now briefly describe the LCCA methodology applied in this study with special attention to the modifications necessary to accommodate our comprehensive approach (FHWA'S methodology is available online at http://restructure.fhwa.dot.gov/dp115/newfull.PDF). A more detailed description of our methodology can be found in Ting et al. [8].

Once alternative pavement designs have been established, the first step of pavement LCCA is to choose an analysis period and discount rate. We chose to use a real discount rate of 4% and an analysis period of 35 years as recommended by the FHWA. The next step is to estimate agency costs for each pavement design. Agency costs include the costs of construction, maintenance, and rehabilitation of pavements. Rehabilitation refers to major repairs and typically occurs once or twice over the course of a pavement's lifetime. Maintenance refers to minor repairs that can happen as often as annually or bianually.

Another important agency cost is residual value, sometimes referred to as salvage value. Residual value is a measure of the economic value of pavements, expressed as a discounted cost, that have service life remaining at the end of the chosen analysis period. Total agency costs are thus the sum of construction, maintenance, and rehabilitation costs over the analysis period, minus the residual value.

The third step is to estimate user costs for each pavement design. User costs are defined by the FHWA as "costs that are incurred by the highway user over the life of the project" [9]. User costs include vehicle operating costs, user delay costs, and crash costs.

Calculation of user costs requires data that were not available for this study, thus we did not include user costs in our LCCA. We acknowledge, however, that user costs associated with construction and major rehabilitation can be significant enough to be a determining factor in economic analyses.

Once agency costs have been estimated, net present value (NPV) is then calculated for each pavement design strategy. As shown in equation 1 below, NPV is a process by which future agency costs (maintenance or rehabilitation) are discounted (using discount rate i) in the year they occur (n), summed together with initial agency costs (construction), and then corrected for any residual value remaining at the end of the analysis period. The result is a total lifecycle cost that reconciles the timing and magnitude of future expenditures with the time value of money.

(equation 1)

$$\text{NPV} = \text{initial cost} + \sum_{n=1}^{N} \left[\text{future cost}_n \bullet \left(\frac{1}{(1+i)^n} \right) \right] - \text{residual value}$$

Residual values are calculated when the last maintenance or rehabilitation included in the analysis extends a pavement's useful life beyond the analysis period. When this situation exists, that future cost is discounted in the year it occurs and multiplied by the fraction of its service life remaining at the end of the analysis period, as described in equation 2 below. This process is a simplified way of calculating annualized costs and follows the method described in FHWA [9] (strict calculation of annualized costs involves discounting each year's average expenditures separately, but that is not the approach adopted in this standardized method).

(equation 2)

when $n+\text{L}_n > \text{N}$,

$$\text{residual value} = \left[\text{future cost}_n \bullet \left(\frac{1}{(1+i)^n} \right) \right] \bullet \left(\frac{(n+\text{L}_n)-\text{N}}{\text{L}_n} \right)$$

where N = final year of analysis period
L_n = service life of future cost_n

It should be reiterated here that pavement LCCA was developed as a tool to compare the costs of alternate pavement designs that deliver equivalent levels of service, i.e. performance. From an engineering standpoint, equivalent pavement designs are those that can support the same number of axle loads over a given period of time. Axle loads are a measure of the weight, quantity, and type of vehicles that are expected to use a given road or parking lot pavement. Starting with a minimum number of "design" axle loads, pavement engineers then typically use the design equations developed by the American Association of State Highway and Transportation Officials (AASHTO) to determine the thickness required for each component of the pavement structure, e.g. the base and surface layers [10]. These design equations require detailed measures of the physical properties of the in situ soils or subgrade and the proposed base and surface layer materials. Such measures include the modulus of elasticity, the modulus of rupture, the modulus of subgrade reaction, the resilient modulus of the subgrade, and the resilient modulus of the base [10].

In the absence of such physical data, there is no strict way to compare alternate pavement structures. However, there is an industry rule-of-thumb that provides first-order approximations of structural equivalency. The design equations for AC pavements include an abstract measure called a structural number (SN), which represents a composite of the physical properties and thickness of each pavement layer. SN is the product of a layer's thickness, structural coefficient (SC), and drainage coefficient (DC). Each layer's SN is then summed to derive the total SN of the pavement structure. When AASHTO engineers were developing AASHTO's design equations in the 1970s, they determined average SC's for AC wearing course, AC binder course (often called blackbase), and crushed stone base course. These values are 0.44, 0.34, and 0.14, respectively [10].

While SC's are not a part of the design equations for PCC, AASHTO engineers did attempt to derive SC-equivalents for PCC. The research yielded estimates ranging from 0.5 to 1.0, and many engineers and PCC-marketers have since been using 0.5 as a conservative estimate of the SC for PCC (Mack, 2000; McMullough, 2000). When comparing AC and PCC pavements in this study, we calculated SN's wherever possible in order to ensure comparison of equivalent pavement structures, to first order.

DATA REQUIREMENTS

Three basic types of data were required for our study: pavement unit cost data, pavement performance data, and pavement albedo data. Pavement unit costs are typically expressed in dollars per square yard and can be separated into material costs and labor costs. Pavement performance "data" take two forms – individual pavement or surface treatment lifetimes and long-term pavement maintenance strategies. Pavement and surface treatment lifetimes measure the service life of full-depth pavements or surface treatments up to the point where significant repair is necessary to maintain a desired level of functionality. The lifetimes used in LCCA are engineering estimates (hence the previous quotations) based on performance data from past projects. Actual lifetimes can vary significantly due to climate, soil conditions, traffic, and construction practices.

Long-term pavement maintenance strategies are the most critical determinant of lifecycle costs and perhaps the most variable. These strategies specify the timing and type of maintenance and/or rehabilitation for a given section or type of pavement over the entire analysis period. Constructing long-term maintenance strategies for comparative purposes such as LCCA is complex. As with pavement lifetimes, these strategies are based on engineering estimates. And although long-term strategies are commonly constructed for budget planning purposes, exactly how strictly such strategies are actually followed is difficult to determine. Deviations from long-term maintenance strategies, of course, significantly affect actual lifecycle costs. In addition to these general estimation issues, another source of variability among strategies comes from the fact that maintenance policies can vary widely. Some agencies take the "don't fix it until it's broken" approach where pavements are allowed to deteriorate significantly before major repair, while some agencies choose to maintain pavements in good condition using more frequent but less costly maintenance treatments.

Although not considered a part of the language of pavements until recently, pavement reflectance is a central part of this study. We characterize pavement reflectance using *albedo* (â). Albedo is defined as the reflectance of a surface averaged over a hemisphere and the solar spectrum. A perfect solar reflector has â = 1, and a perfect absorber has â = 0. Pavement albedos vary from region to region (and even within regions) due to differences in the albedos of the constituent materials. Pavement albedos also vary over time due to weathering, oxidation at the pavement surface, dirt and dust accumulation, tire wear, and oil deposits. Surface repairs also change pavement albedos dramatically. Still, two generalizations can be made concerning how pavement albedos change over time. First, AC pavements all start off black with albedos around 0.05 and get lighter over time, usually approaching 0.12 (see Pomerantz, 1999a THIS REFERENCE DOESN'T EXIST IN THE LIST AT THE END). Second, PCC pavements all start off fairly light with albedos around 0.35 and get darker over time, approaching 0.25 (see [11]). Given enough data about pavement albedo and age, one can construct a relationship of pavement albedo over time. For this study, we used data collected by LBNL to construct such a relationship, the derivation and application of which is detailed in Ting et al. [8].

DATA SOURCES & AVAILABILITY

As 95% of urban pavements in the United States are AC [12], we were able to gather comprehensive cost and performance data for AC and asphaltic surface treatments with relative ease (the situation is quite different for interstate freeways, highways, and bridge decks where the split between AC and PCC is much more even), Obtaining similar data for PCC and other pavement types proved more difficult and required the use of multiple data sources. Our primary sources for cost and performance data were the Metropolitan Transportation Commission's (MTC) Pavement Management System (PMS), the RS Means family of construction cost data books, and pavement contractors. We supplemented these sources with historical performance estimates from municipal agencies, pavement product manufacturers, and engineers at the American Concrete

Pavement Association (ACPA). All the data sources used in this study are detailed in Ting et al. [8].

The albedo data used in this study all come from direct measurements taken by LBNL [6]. For AC pavements, the data set is comprised of 38 field measurements each with a corresponding pavement age. For PCC pavements, we use a similar set of 18 measurements taken in the field. Albedo measurements of colored asphalt seal coats were limited to those taken from a local demonstration site. Measurements for resin pavements were limited to a set of lab samples provided by the manufacturer.

III. ESTIMATING THE DURABILITY BENEFITS OF HIGH-ALBEDO AC PAVEMENT

In this section, we provide a brief overview of the existing scientific evidence that supports the notion that lowering maximum surface temperatures will significantly increase the durability of AC pavements. We then propose three methods to increase the albedo of AC pavements and describe how we apply preliminary estimates of increased AC durability to the lifecycle cost analyses of those proposed methods.

In 1987, Congress established the Strategic Highway Research Program (SHRP), a five-year $150 million research effort to improve the performance, durability, and safety of U.S. roads. The final product of SHRP's asphalt research program was a system called SUPERPAVE (SUperior PERforming asphalt PAVEments) which established a new specification system for the components of AC, improved AC mix designs, and improved AC pavement performance prediction, all aimed at improving the overall performance and durability of AC. The binder specifications that emerged from SUPERPAVE use maximum and minimum pavement temperatures as the key parameters for determining the binder's required "performance grade". Specifically, higher maximum pavement temperatures require higher "performance grade" binders [13].

These specifications prominently acknowledge the importance of pavement temperature ranges, i.e. yearly maxima and minima, on the durability of AC pavement. To maintain performance over a wide range of temperatures (which is difficult for typical AC), SHRP's solution is to enhance binders with polymer additives; this makes the binder more expensive. A recent LBNL study [14] has taken a different approach – lowering maximum pavement temperatures (via increased reflectivity) as a way to shrink pavement temperature ranges and improve AC durability. Specifically, the study used laboratory testing methods to establish a first order relationship between maximum pavement temperature and common AC pavement distress mechanisms, namely rutting and shoving. The results indicated a strong relationship between increases in pavement temperature and accelerated failure rates due to rutting and shoving. This exponential relationship was demonstrated over a limited range of temperatures (40ºC, 50ºC, 60ºC). It should be noted, however, that these temperatures are representative of seasonal maximum temperatures experienced in the major heat island cities of the U.S.

A study by the California Department of Transportation on the relationship of temperature and embrittlement in AC pavements (a common cause of pavement cracking) yielded similar conclusions. Hardening rates were found to accelerate at higher temperatures, indicating a strong, non-linear relationship between pavement temperature and embrittlement [15].

The results, however convincing, must be taken in context. The laboratory environment did not account for possible mitigating factors such as the cooling effects of vehicles (through shading and stirring of the surrounding air) and tire wander. Still, any increase in pavement lifetime reduces lifecycle costs, and thus we wish to incorporate the effect to some extent in our economic analysis. In order to do so, we have established a preliminary method to approximate the increase in AC pavement lifetime resulting from increases in AC pavement albedo. The method is overtly conservative in that the strong, non-linear relationship described by the laboratory results is represented by a linear relationship. Ting et al. [8] describes the method in detail.

For this study we consider four methods to increase the albedo of AC pavements. The first method we propose is the use of high-albedo chip seals in conjunction with AC and AC overlays, which we shall refer to as the “chip seal method”. Chip seals are non-structural surface treatments that consist of spreading and rolling small open-grade aggregates, or ”chips”, onto a layer of asphalt emulsion. Chip seals are commonly used on low-volume roads as a means to protect the underlying pavement from moisture intrusion and oxidation at the pavement surface while also providing enhanced skid resistance. In addition to using high-albedo chips in chip seals, we propose applying such chip seals in conjunction with the installation of AC and AC overlays. Since the top layer of chips are immediately exposed, this chip seal method would tend to immediately maximize the durability benefits provided to the underlying pavement from lower surface temperatures.

The second method we consider is the use of light-colored additives in asphalt emulsion sealcoats. Sealcoats are applied to AC parking lot pavements on a regular basis to prevent moisture intrusion and oxidation at the surface as well as to maintain appearance. Light-colored emulsion additives are available for decorative applications, and we propose using them in conjunction with newly constructed parking lots so as to immediately maximize the durability benefits provided to the underlying pavement from lower surface temperatures.

The third mechanism we consider is the “chipping” of new AC pavements and overlays with high-albedo chips, which we shall refer to as the “chipping method”. Although not currently used in the U.S., chipping is a common practice in Great Britain as a means to provide skid resistance [16]. Chipping differs from chip sealing in that the chips are bitumen-coated and rolled directly into fresh AC before the binder sets without using an additional layer of asphalt emulsion. If new AC pavements and overlays were chipped with uncoated high-albedo chips, the top layer of chips would then be immediately exposed. As with the chip seal method, the chipping method would tend to immediately maximize the durability benefits afforded to the underlying pavement resulting from reduced surface temperatures.

The fourth mechanism involves substituting high-albedo aggregates for conventional aggregates in full-depth AC and AC overlays, which we shall refer to as the "aggregate method". In this method, asphalt binder would initially coat the aggregates, therefore we must take into account the lag time between the installation of new AC and the time when constituent aggregates become exposed at the surface. Derivation and application of this lag time is described in Ting et al. [8].

IV. DEVELOPMENT OF PAVEMENT LIFECYCLE SCENARIOS

This section describes the development of the long-term maintenance strategies used for calculating lifecycle costs in this study. We first describe the development of what we determined to be the most likely range of long-term maintenance strategies applied to conventional AC pavements in major U.S. cities. We then isolate the appropriate conventional AC "base cases" against which to compare reflective pavement alternatives and describe the long-term maintenance strategies developed for those reflective alternatives. For the remainder of this report, we use the term "lifecycle scenario" to describe the construction and/or long-term maintenance of a given pavement over the analysis period.

CONVENTIONAL AC STREET SCENARIOS

The information in MTC's PMS [17] allowed us to develop 42 lifecycle scenarios for conventional AC streets. The determining parameters in each scenario were based on functional class and beginning and ending (or terminal) pavement condition. MTC uses a Pavement Condition Index (PCI) designed specifically for the Bay Area that allows them to compile pavement condition information in a uniform manner. PCI is a numerical rating of pavement condition. Pavement condition information, such as roughness and the types and severity of existing pavement distress, is collected in the field by technicians and used to calculate a weighted index scaled to 100. Pavements with PCI's of 70-100 are considered to be in "very good to excellent" condition, those with PCI's of 50-70 are in "fair to good" condition, those with PCI's of 25-50 are in "poor to fair" condition, and those with PCI's of 0-25 are in "poor" condition. There is also a distinction within the 50-70 range between the existence of "load-related" distress (e.g., rutting and shoving) and "non-load related" distress (e.g., cracking and weathering). This distinction is necessary because the repair of load-related distress is significantly different from that of non-load related distress. We use PCI to represent different maintenance policies in that we construct scenarios that reflect "don't fix it until it's broke" policies, policies that maintain streets in very good condition, and versions in between. We also use PCI to differentiate pavements that experience load-related distress from pavements that experience non-load related distress.

We developed lifecycle scenarios for each functional class of urban streets – arterial, collector, and residential. To account for differences in pavement maintenance policies, we consider that these streets could be maintained at different levels of deterioration (as measured by PCI) depending on the maintenance practices of local agencies. To do this, we developed one set of scenarios based on a terminal PCI of 70, another based on a terminal PCI of 50, and another based on a terminal PCI of 50 with load-related distress. For example, we begin with an arterial street whose PCI is 70-100 and choose a terminal PCI of 70. The MTC PMS states that the PCI will deteriorate from 70-100 to 70 after 7 years. The PMS then recommends application of a slurry seal. This treatment maintains the pavement's PCI above 70 for another 7 years. At year 14, the PMS then recommends a thin AC overlay. This overlay maintains the PCI above 70 for the following 8 years. At year 22, a slurry seal is again applied which maintains the pavement's PCI above 70 for another 7 years. Finally, at year 29, the pavement surface is milled and a thin overlay is placed which maintains the pavement's PCI over 70 through the end of the 35-year analysis. Following these PCI-based "lifetimes" and treatment sequences of the MTC PMS, we apply the same approach to the other functional classes and terminal PCI's. To the best of our knowledge the three terminal PCI's we have chosen (70, 50, and 50 with load-related distress) represent the most common pavement maintenance policies.

To further develop the range of scenarios for existing streets, we also consider that streets could be in varying states of deterioration at the beginning of the analysis period. This is done by letting the starting pavement condition vary from "very good" to "poor" using four different starting PCI's. Varying the starting PCI influences the choice and timing of only the first treatment in the analysis period and thus mainly influences the pavement's initial costs. For example, in an arterial street scenario with a starting PCI of 70-100 and terminal PCI of 70, the first treatment of the analysis period (a slurry seal) occurs only after the PCI has declined below 70 (year 7). If we change the starting PCI to 25-50, MTC's PMS recommends a different first treatment (a thick AC overlay) and that this treatment occur in the very beginning of the analysis period (year zero) since the terminal PCI is 70. In this way, varying the starting PCI's allows us to evaluate the likely range of initial costs (mostly dependent on original pavement condition), whereas varying the terminal PCI's allows us to evaluate the likely range of future costs (mostly dependent on maintenance policy).

In total, the result is a set of 4 different starting points within each of the three "maintenance policy" frameworks, applied to each of three functional classes, which totals 24 different lifecycle scenarios for existing, conventional AC streets.

We also developed lifecycle scenarios that describe reconstructed pavements where adequate pavement performance cannot be easily maintained without completely rebuilding the pavement. These can be thought of as new pavements that replace old, unserviceable pavements. In these scenarios, the analysis periods all begin with the reconstruction of the pavement. Using the same terminal-PCI approach, we developed one set of scenarios based on a terminal PCI of 70, another based on a terminal PCI of 50, and another based on a terminal PCI of 50 with load-related distress. We also differentiated starting points by separating totally reconstructed streets, i.e. surface and base reconstruction, from streets with only surface reconstruction. (surface reconstruction differs from "surface rehabilitation" techniques like milling and hot-mix overlays in that surface reconstruction involves complete removal and replacement of the pavement layers above the base course). This was necessary because the cost and service lives of totally reconstructed streets are much higher than those of surface reconstructed streets. Developing these sets for each of the three functional classes results in 18 different lifecycle scenarios for reconstructed conventional AC streets.

Together, the above lifecycle scenarios represent our approximation of the most likely range of AC street pavement lifecycles that occur in major cities.

HIGH-ALBEDO AC STREET SCENARIOS

We developed lifecycle scenarios for high-albedo AC streets based on those developed for existing and reconstructed conventional AC streets. We apply our lifetime extension estimates to the lifetimes of AC pavements and AC overlays. We do not apply lifetime extensions to non-structural surface treatments (e.g., slurry seals or pothole patching). The methods to increase the albedo of AC street pavements considered in this study are partly conceptual and/or not currently used in the U.S. Therefore, we must make assumptions about what levels of increased albedo would likely be achievable in order to estimate the extended pavement lifetimes afforded by reductions in pavement surface temperature. We chose to evaluate high-albedo AC pavements using two levels of increased albedo, $\Delta\hat{a}=0.1$ and $\Delta\hat{a}=0.2$.

We base our lifecycle scenarios for high-albedo AC streets on the load-related distress scenarios developed for conventional AC streets, i.e. those whose terminal PCI is 50 with load-related distress. We chose to only use the load-related distress scenarios primarily because the evidence behind increased durability of high-albedo AC is highly preliminary and what evidence exists is linked to the mitigation of load-related distresses, i.e. rutting and shoving, in addition to climate-related embrittlement. We therefore do not attempt to claim durability benefits outside of the parameters described by Pomerantz *et al.* [14] and Kemp and Predoehl [15].

We first evaluate lifetime extension estimates for AC overlays and reconstructed AC resulting from the chip seal, chipping, and aggregate methods at albedo increases of both $\Delta\hat{a}$=0.1 and $\Delta\hat{a}$=0.2. These lifetime extension estimates are then applied to all AC overlays and AC reconstruction that occur in the lifecycle scenarios previously developed for streets with load-related distress.

Following this process for each functional class and differentiating between existing, surface reconstructed, and totally reconstructed streets gives us a total of 36 lifecycle scenarios for high-albedo AC streets. We chose to apply the chip seal method only to existing streets and the chipping method only to reconstructed streets. The aggregate method was applied to both existing and reconstructed streets. The sealcoat method was only applied to parking lots.

PCC AND WHITETOPPED STREET SCENARIOS

As discussed earlier, MTC's PMS does not contain estimates of the lifetimes or maintenance strategies for PCC or ultra-thin whitetopping (UTW). However, the long-term maintenance and performance of full-depth PCC pavements tends to vary only slightly across functional classes, thus the range of likely lifecycle scenarios is much smaller than that for AC pavements. Based on information obtained from contractors, ACPA engineers, and municipal pavement managers in Seattle and Houston, we developed one lifecycle scenario for each functional class resulting in three lifecycle scenarios for full-depth PCC street pavements. In the attempt to compare structurally-equivalent AC and PCC pavements, we considered PCC pavement designs with structural numbers of 6, 5, and 4.5 for arterial, collector, and residential streets, respectively. These structural numbers imply plain jointed PCC pavement depths of 12", 10", and 9" for arterial, collector, and residential streets, respectively.

We were afforded even less detail in developing lifecycle scenarios for whitetopped streets due to a lack of historical data on whitetopping performance over various starting pavement conditions or functional classes. Based on information from contractors in Missouri and Kansas and engineers at ACPA, we developed two lifecycle scenarios that represent the most common application of whitetopping in city streets today – the rehabilitation of severely distressed AC intersections using 4" UTW and the surface reconstruction of AC streets using 3" UTW (Missouri and Kansas along with Tennessee have the majority of installed whitetopping in the U.S. For more information on the state of whitetopping in the U.S., visit the ACPA website at http://www.pavement.com/). In order to fairly compare the lifecycle costs of whitetopping against conventional AC, we also developed lifecycle scenarios for reconstructing distressed AC streets (using the same method described previously for conventional AC) and a severely distressed AC intersection (using frequent conventional AC overlays).

PARKING LOT SCENARIOS

For parking lots, developing lifecycle scenarios for LCCA is more straightforward than for streets. Generally, parking lots are maintained by private firms that rely on contractor-recommended practices to determine how and when to rehabilitate their pavements. Parking lot maintenance is often based on maintaining appearance as well as performance, so parameters like pavement condition do not necessarily determine how those pavements are maintained. For this study, we developed lifecycle scenarios for parking lots based on past studies and recommendations from contractors. In the case of porous pavements and resin pavements, we put together scenarios based on manufacturer-recommended practices.

We developed 17 lifecycle scenarios for parking lots: three conventional AC scenarios, three PCC scenarios, three porous pavement scenarios, one resin pavement scenario, six high-albedo AC scenarios, and one whitetopping scenario. All of the lifecycle scenarios begin with construction of the pavement and, where possible, assume a structural number of 2.5. The three conventional AC scenarios differ in the timing and type of maintenance or rehabilitation applied and represent our upper bound, best guess, and lower bound estimates. The same applies to the three PCC scenarios. The lifecycle scenarios for porous pavements differ only in the costs of construction, which mainly reflects differences in the costs of the lattice units and the constituent materials used for base courses. The lifecycle scenario for resin pavements is based on typical maintenance for AC parking lots but with different construction costs.

We consider one mechanism to increase the albedo of AC parking lots – the sealcoat method described earlier (Chipping and chip sealing are not used as surface treatments in parking lots and are thus not considered in our high-albedo scenarios for parking lots.). We base our lifecycle scenarios for high-albedo AC parking lots on those developed for conventional AC. Assuming that sealcoats enhanced with light-colored additives are applied during initial construction, we apply our lifetime extension estimates to the underlying AC pavement using no lag time. We consider two levels of increased albedo ($\Delta\hat{a}$=0.1 and $\Delta\hat{a}$=0.2) within each scenario (lower bound, best guess, and upper bound), yielding a total of six lifecycle scenarios for high-albedo AC parking lots.

V. RESULTS OF PAVEMENT LIFECYCLE COST ANALYSES

CONVENTIONAL AC STREETS

We present first the results of our LCCA's for conventional AC streets. These results are based mainly on the information obtained from MTC's PMS; therefore the results are specific to pavements in the San Francisco Bay Area and should not be interpreted as representative for all major cities. All costs are expressed in 2000 dollars.

The results of our LCCA's for existing, conventional AC streets are summarized in **Figures 1 and 2.** The results are presented this way so as to illustrate the relative magnitudes of the lifecycle costs of existing AC streets across starting PCI, terminal PCI, and functional class. From Figures 1 and 2, we can see that there is little difference between the lifecycle costs of AC arterial streets and AC collector streets, but the lifecycle costs of AC residential streets are significantly lower. We can also see that the relative costs of arterial and collector streets starting in "good to fair" and "fair to poor" condition are much higher than those starting in “very good” condition. Another important observation is that streets with load-related distress have significantly higher lifecycle costs than similar streets with nonload-related distress.

{Figure 1}

{Figure 2}

{Figure 3}

The results of our LCCA’s for reconstructed AC streets are summarized in **Figure 3**. We can see from Figure 4 that the difference in lifecycle costs between arterial and collector streets is significant for reconstructed streets, which was not the case for existing streets. Additionally, we see that the effect of varying the terminal PCI has less of an impact on the costs of reconstructed streets than existing streets.

HIGHER REFLECTIVITY STREETS

We now summarize the results of our LCCA’s comparing conventional AC street pavements to alternatives with higher reflectivity. Two important comments about interpreting these results. First, the scenarios comparing conventional AC and reflective pavement alternatives describe prices and weather conditions in Los Angeles (as opposed to San Francisco). Qualitatively, we chose LA mainly because it is a more significant heat island than San Francisco, but also because the smog- and energy-savings potential from the use of reflective pavements has been previously estimated by researchers at LBNL [18]. Thus, our results can be set in a relevant context with previous heat island research. Quantitatively, we have chosen to use data for Los Angeles in our calculations because the lifetime extension estimates applied to the high-albedo AC scenarios are city-specific (see [8]). (We obtained enough weather data to estimate AC pavement durability benefits from increased-albedo for Phoenix, Houston, Sacramento, New Orleans, Salt Lake City, Atlanta, and Miami, BUT DIDN’T DO SO IN THIS STUDY?????.) As such, we have also scaled the unit costs from MTC's PMS and the RS Means databooks to LA prices. All costs are expressed in 2000 dollars.

Second, we were unable to reasonably estimate the incremental costs of using high-albedo aggregates in the high-albedo AC scenarios. In our calculations, we were therefore forced to assume no incremental costs associated with using the aggregate, chip seal, and chipping methods in our LCCA's. In order to interpret the results of our high-albedo AC scenarios correctly, we present a "delta cost" for each high-albedo AC scenario which is the cost difference from the "base case" (conventional AC) scenario. These "delta costs" are negative and are best interpreted as an approximation of the allowable incremental cost of using high-albedo aggregates that permits high-albedo AC to be cost-effective compared to conventional AC. Large delta costs therefore represent better opportunities for cost-effectiveness than small delta costs. If it is the case that high-albedo aggregates are readily available for little or no incremental cost, the "delta costs" then represent the range of lifecycle cost savings potentially afforded by high-albedo AC. In the absence of such knowledge, however, it is more appropriate to consider these "delta costs" as the allowable margins for cost-effectiveness compared to conventional AC. Note that these "delta costs" are not expressed for full-depth PCC, ultra-thin whitetopping, porous, or resin pavements since all the costs of these pavements were known and referenced. All lifecycle cost results are displayed using three significant digits.

Our results for existing streets comparing the lifecycle costs of conventional AC to the lifecycle costs of high-albedo AC using the aggregate method and the chipseal method are shown in **Table 1**.

{Table 1}

From Table 1, we observe that the increased AC pavement lifetimes afforded by increases in albedo appear to have a significant impact on lifecycle costs. For arterial and collector streets, the delta costs are ~\$2/SY (~\$2.40/m^2). For residential streets, the delta costs are much less, averaging approximately ~\$0.60/SY (~\$0.70/m^2). This difference reflects the fact that residential streets have lower initial costs and longer expected lifetimes than arterial and collector streets. Thus, potential increases in AC lifetime have a smaller impact on the lifecycle costs of residential streets compared to arterial or collector streets when evaluated over a 35-year period. Table 1 also suggests that for existing streets, the aggregate method has approximately the same impact on lifecycle costs as the chipseal method, despite the lag time associated with the aggregate method.

Table 2 presents the results of our whitetopping LCCA for existing streets. Currently, the most common application of whitetopping is the rehabilitation of distressed AC intersections. For comparison, we developed a lifecycle scenario for a conventional AC intersection requiring overlays every four years (see [8]). Since the real-world lifecycle of whitetopping is still unknown, we also scale the analysis periods of the whitetopped and conventional AC intersection scenarios to the current "design life" of whitetopping, 20 years. From information gathered from contractors and ACPA engineers, we determined that using analysis periods over 20 years to evaluate the lifecycle costs of whitetopping is problematic since there is still very little real-world experience with "post-whitetopping" rehabilitation.

{Table 2}

From Table 2 we observe that the lifecycle costs of an intersection rehabilitated with whitetopping are approximately \$1/SY (~\$1.20/m^2) lower than those of an intersection rehabilitated with conventional AC overlays. Given the amount of uncertainty involved in this comparison, however, a more reasonable observation is that the lifecycle costs of the two rehabilitation approaches appear to be very close. There are significant differences in future costs between the two approaches, however. This difference reflects the low-maintenance requirements of whitetopping versus the high frequency of AC overlays. Although we do not calculate user costs in this study, it is safe to assume that the work zone user costs of the AC overlay approach, resulting from rehabilitation work every four years, would be much higher than those of the whitetopping approach since little to no maintenance or rehabilitation has been necessary over the design life of existing whitetopping projects.

We now summarize our LCCA results for reconstructed streets. First we present the results for totally reconstructed streets (which includes base layer reconstruction) and compare the lifecycle costs of total reconstruction with conventional AC, plain jointed PCC, and high-albedo AC using the aggregate method and the chipping method. Again, we use Los Angeles as our example city and scale unit costs to Los Angeles prices. For conventional and high-albedo AC, we compare results based on "load-related distress" lifecycle scenarios. The results are shown in **Table 3**.

{Table 3}

From Table 3 we again observe that the increased AC pavement lifetimes afforded by increases in albedo appear to have a significant impact on lifecycle costs. For arterial and collector streets, the delta costs are between \$5-\$11/SY (\$6-\$13/m^2) with the exception of the Δâ=0.1 scenarios using the aggregate method which exhibit delta costs of only ~\$1/SY. These scenarios suggest that for reconstructed streets, the impact of the aggregate method's lag time could significantly compromise potential lifecycle cost savings. For residential streets, the delta costs of high-albedo AC are much larger for reconstructed streets than for existing streets. This is because the initial costs of reconstructed residential streets are much higher than those of existing residential streets.

From Table 3 we also observe that the lifecycle costs of full-depth PCC streets appear to be \$2-\$6/SY (\$2-\$7/m^2) less than those for conventional AC. This result, although consistent with what we expect, contains large uncertainties, as we were unable to establish strict structural equivalency between these pavements due to a lack of information on the structural designs of totally reconstructed AC pavements as described in MTC's PMS.

Our LCCA results for surface reconstructed streets are presented in **Table 4**. We compare the lifecycle costs of surface reconstruction with conventional AC and high-albedo AC using the aggregate method and the chipping method. We scale unit costs to LA prices and base comparisons on “load-related distress” lifecycle scenarios. From Table 8 we observe that the delta costs of high-albedo AC in surface-reconstruction scenarios are ~$1-2/SY and that the aggregate method yields approximately the same lifecycle cost benefit as the chipping method.

{Table 4}

In **Table 5**, we compare the lifecycle costs of total and surface reconstruction with conventional AC to the lifecycle costs of rehabilitation with whitetopping. Again, a 20-year analysis period is used in the comparison due to the uncertainty of the longer-term lifecycle of whitetopping.

{Table 5}

From Table 5 we observe that the lifecycle costs of whitetopping are much lower than those of total reconstruction with conventional AC but $2-9/SY ($2-11/m^2) greater than those of conventional surface reconstruction. Again, due to the uncertainty involved, a reasonable conclusion would be that the lifecycle costs of whitetopping are in the range that provides a cost-effective alternative to the total reconstruction of AC streets. Second to the rehabilitation of AC intersections, whitetopping’s most common application today is as an alternative to reconstructing distressed AC streets.

PARKING LOTS

We now summarize the LCCA results for parking lot pavements. We compare the lifecycle costs of conventional AC, plain jointed PCC, porous pavement, resin pavement, and high-albedo AC using the sealcoat method. We also present the results of a parking lot reconstruction scenario comparing conventional AC and whitetopping. All lifecycle scenarios used in the parking lot comparisons begin with construction of the pavement and assume 35-year design lives (i.e., no residual values) with the exception of the reconstruction scenarios, which are scaled to the 20-year design life of whitetopping. Unlike our LCCA's for street pavements, we include the cost of "striping" (painting parking stalls) in our parking lot LCCA's since parking lots are restriped with much higher frequency than streets and as such restriping can have an impact (albeit small) on the long-term maintenance costs of parking lots.

Tables 6 and 7 show the results of our parking lot LCCA's. Full-depth PCC exhibits the lowest lifecycle costs, followed by conventional AC. Whereas the initial costs of PCC are slightly higher than conventional AC, the future costs of PCC are much lower and result in lower lifecycle costs. The lifecycle costs of high-albedo AC are higher than conventional AC in our parking lot scenarios due to the incremental cost of using high-albedo sealcoats. These light-colored asphalt emulsion sealcoats are currently used as decorative treatments and are up to \$3/SY (\$3.60/m^2) more expensive than the standard emulsion sealcoats commonly used on parking lot pavements.

{Table 6}

Resin pavements exhibit fairly low lifecycle costs in our analysis. These results should be interpreted with caution, however, due to the uncertainty in unit costs, long-term performance, and maintenance. Currently, resin pavements are used mostly as historical walkways and bikeways, and little is known about their performance as parking lot pavements. Laboratory tests indicate that the strength of resin pavements is equivalent to AC pavements, but data on long-term performance and maintenance are not yet available.

Porous pavements exhibit the highest lifecycle costs in our parking lot analyses. There is an important caveat to note, however, in that the primary cost benefit of porous pavements did not fall within the boundaries of our LCCA's. Reduced storm water management is one of the primary cost savings of porous pavements, since the need for extensive drainage systems is greatly reduced by draining runoff directly into the ground.

We could not include drainage systems in our LCCA's because the design and resulting costs of such systems are dependent on factors which we could not account for in a comprehensive manner such as annual rainfall, parking lot size, and proximity to secondary sources of runoff. In terms of heat island mitigation, porous pavements also provide the additional benefit of increased grass cover, which can serve to cool surrounding air directly via evapotranspiration.

Table 7 compares the lifecycle costs of parking lots reconstructed with conventional AC to those rehabilitated with whitetopping. Again, the analysis period is reduced to 20-years to reflect the design life of whitetopping. The results indicate that the lifecycle costs of whitetopping are significantly lower than reconstructing a parking lot with conventional AC.

{Table 7}

In all our whitetopping comparisons, it is clear that whitetopping is a cost-effective alternative to reconstruction with conventional AC. It should be noted, however, that this comparison is only valid when conventional AC pavements have reached the end of their design lives and/or suffered significant pavement distress, particularly rutting and shoving. In these situations, conventional AC rehabilitation such as AC overlays have already run their course and the only remaining option is to reconstruct. This is the particular market niche in which whitetopping currently competes. It provides a medium-term alternative to AC pavement reconstruction (and defers those costs for up to 20 years), and, in the case of severely distressed AC, it provides a reliable structural rehabilitation for pavement sections prone to severe rutting and shoving.

VII. FUTURE WORK

Through the course of this study, we identified several data sets and estimation issues that affect the economic analysis of pavements and the comprehensive evaluation of reflective pavements as a heat island mitigation measure. We discuss the future work required to address these evaluation issues below.

What is the lifecycle of whitetopping?

Because whitetopping is a still a maturing technology, existing projects have yet to firmly establish the expected service life or optimal maintenance strategies for both conventional and ultra-thin whitetopping. Detailed cost and performance tracking of whitetopping projects is necessary in order to reconcile engineering predictions with real-world performance. Since we know that the performance of AC pavements varies depending upon functional class, it is also necessary to track projects by function, i.e. intersections vs. parking lots vs. streets, in order to determine how whitetopping performance varies.

What PCC pavement structures are most appropriate for comparing the lifecycle costs of different street pavements?

Due a lack of information about the structural designs of arterial, collector, and residential AC streets described in MTC's PMS, we were forced to assume that full-depth PCC pavements with structural numbers of 6.0, 5.0, and 4.5 were structurally equivalent to their AC counterparts. In the absence of site-specific data on the physical properties of in situ subgrades and soils, it is necessary to determine what PCC pavement structures are most appropriate for the comprehensive comparison of lifecycle costs across functional classes and design options.

How do the albedos of pavements and surface treatments change over time?

The albedo data sets used in this study did not include any measurements of common surface treatments like chip seals, slurry seals, or emulsion seal coats. To be able to accurately estimate the evolution of a pavement's albedo over its entire service life, it is necessary to know how albedo varies with the age of surface treatments. This can be done by measuring the albedo of pavements where the age of the surface treatment is known. Ages can be determined from contract records. Our albedo data set was also limited to pavements in the San Francisco Bay Area. Since we know that pavements age differently in different climates, it is also necessary to measure how pavement albedos change in other climates.

How much do the albedos of AC and PCC vary from region to region?

Again, since our albedo data set was limited to local pavements, it is necessary to determine if pavement albedos are significantly different in other regions of the country. From the information we obtained regarding regional production of different types of aggregates, we know that the aggregates used in Texas pavements are different from those used in San Francisco pavements, but exactly how much those pavements differ regionally in terms of albedo needs to be determined from direct measurements

How do reductions in maximum surface temperature affect the durability of AC?

The results of Pomerantz et al. [14] indicate a strong, non-linear relationship between reduced surface temperature and increased AC pavement lifetime before failure due to rutting, shoving, and embrittlement. Based on these conclusions we established a preliminary method to estimate the durability benefits of high-albedo AC for the purpose of incorporating those benefits into our economic analyses. Since we have shown that those benefits can indeed have a significant impact on lifecycle costs, it is necessary to refine our estimates by making additional field or accelerated laboratory measurements of the relationship between maximum surface temperatures and AC pavement lifetime.

How much can the albedo of AC be increased by using high-albedo aggregates?

In this study, we proposed three mechanisms to increase the albedo of AC pavements through the use of high-albedo aggregates – the aggregate method, the chip seal method, and the chipping method. We assumed that these mechanisms would produce increases in albedo of 0.1 and 0.2. The extent and longevity of potential increases in albedo from these mechanisms under real-world conditions should be explored.

What are the incremental costs of using the highest-albedo aggregates available?

For our current economic analyses, we assumed no incremental costs associated with using high-albedo aggregates in AC. This assumption implies not only that high-albedo aggregates are available, but that they are located within 25 miles of the project (beyond which additional surcharges are usually applied). While we were able to find comprehensive aggregate production information by type and region from the U.S. Geological Survey, we could not reasonably estimate corresponding albedos without direct measurements and therefore could not determine what the potential incremental costs of using relatively high-albedo aggregates might be. In order to estimate the potential heat island benefits of using such aggregates in AC pavements, we must know the albedos of aggregates currently used for AC pavements and the albedos of the lightest-colored aggregates available in the region, if any. Similarly, in order to estimate the incremental costs of using high-albedo aggregate in AC pavements, we must also know the sources of both conventional and high-albedo aggregates. The application of a geographic information system to address these estimation issues should be explored.

What are the potential market penetration rates of reflective pavements and what are realistic energy- and smog-reduction potentials over time?

Current estimates of the energy- and smog-reduction potential from using reflective pavements are based on 100% market penetration. These estimates do not attempt to clarify the amount of time necessary to achieve 100% penetration. Given that economic arguments could be made for the use of reflective pavements or that policy mechanisms could be put in place to promote reflective pavements, it is necessary to estimate heat island reduction potentials over time using realistic penetration rates. This would not only frame the estimates in real-world parameters but provide planners and regulators with useful information.

VII. SUMMARY

In this study, we calculated and compared the lifecycle costs of conventional AC and several reflective pavement technologies in the context of their use in urban streets and parking lots. We also assessed the primary market barriers associated with reflective pavement technologies. Our findings are summarized in **Table 8** and we discuss those findings below.

Full-depth PCC and high-albedo AC pavements exhibited the lowest lifecycle costs in our study. However, our cost estimates of full-depth PCC, although consistent with what we expected, contain large uncertainties due to the fact that we could not firmly establish that we were comparing equivalent pavement structures. Despite these uncertainties, however, full-depth PCC pavement is a proven technology that is used extensively in several major U.S. cities. PCC is the strongest pavement technology known today and is best suited for areas with high truck volumes as exhibited by its frequent use in bridge decks, interstates, and elevated highways. However, PCC is also used in low-volume areas because of its low maintenance requirements. The most significant market barrier to full-depth PCC pavements is its high first cost when compared to conventional AC. This barrier is augmented by the fact that county and municipal agencies are often constrained by first costs. Moreover, developers who build new roads and are not held accountable for the long-term maintenance of newly constructed roads tend to choose low first-cost pavement designs so as to maximize profit margins. At the project level, non-uniform strength or compaction of base soils and frequent utility cutting can also pose significant barriers to the use of full-depth PCC pavements.

Whitetopping also exhibited low lifecycle costs when compared to reconstructed and frequently-rehabilitated AC pavements. Whitetopping is a rapidly maturing technology with over 150 installations currently in city streets. Although the cost estimates used in our comparisons were confirmed by contractors and industry experts, we were forced to shorten the analysis period from 35 years to 20 years because of the uncertainty involved in estimating post-whitetopping paving options. Still, our results indicate that whitetopping is a cost-effective alternative to reconstructing conventional AC pavements and a cost-effective option for rehabilitating AC pavements prone to rutting and shoving distresses.

Our estimates of the lifecycle costs of increased-albedo AC pavements were the lowest of all the alternative pavement technologies considered. However, these estimates did not attempt to estimate the full incremental costs associated with these approaches because we could not reliably estimate the incremental cost of using high-albedo aggregates and chips. Thus the lifecycle cost savings implied by our results are better interpreted as approximations of the allowable incremental costs (delta costs) of using high-albedo aggregates that would permit these approaches to be cost-effective compared to conventional AC. From a technical perspective, chip sealing is already a common maintenance treatment used on AC pavements throughout the U.S. The chipping method is used extensively in Great Britain and while it is not currently optimized for reflectivity, the practice and method are well developed. In contrast, the proposed aggregate method is currently a conceptual approach and has yet to be tested in the field. Similarly, the use of uncoated chips in the chipping method is novel and needs testing. Still, both the aggregate method and the chip seal method do not require significant changes to current AC paving practices, and in that respect seem readily accessible once proven to be effective. Moreover, the evidence of increased AC pavement durability from decreased pavement surface temperature is convincing enough to warrant further investigation into these simple approaches. If the incremental costs of these pavements are indeed low and the durability benefits produce significant increases in pavement lifetimes, the lifecycle costs of these pavements would be significantly lower than conventional AC in cities with major heat islands.

The lifecycle costs of porous pavements and AC pavements using asphalt emulsion sealcoats with light-colored additives were higher than conventional AC pavements. In the case of porous pavements, some key cost savings fell outside the boundaries of this study (i.e., reduced storm water management) which, if considered, could lower the lifecycle costs significantly relative to conventional AC. Because of their grass and/or gravel surfaces, porous pavements are not suitable high-volume applications like streets or public parking lots, but they are suitable for low-volume applications such as overflow parking and emergency access lanes. Light-colored asphalt emulsion additives are an existing technology, but the incremental costs associated with them are significant. Because its existing market is decorative applications, the technology has not been optimized for reflectivity or high traffic-volume applications. However, given the development of a light-colored asphalt emulsion additive with lower incremental costs, its use in parking lot applications requires no changes in current paving practices other than choosing an alternative sealcoating product. As asphalt emulsion color additives gain market share, it is expected that their costs will come down over time.

Finally, the lifecycle costs of resin pavements, while only slightly higher than conventional AC, were the most uncertain of all the pavements considered in terms of unit costs, long-term performance, and maintenance. Laboratory tests indicate that the strength of resin pavements is equivalent to that of AC pavements. However, the performance of resin pavements in streets is still untested and few parking lot installations currently exist to provide reliable performance estimates.

{Table 8}

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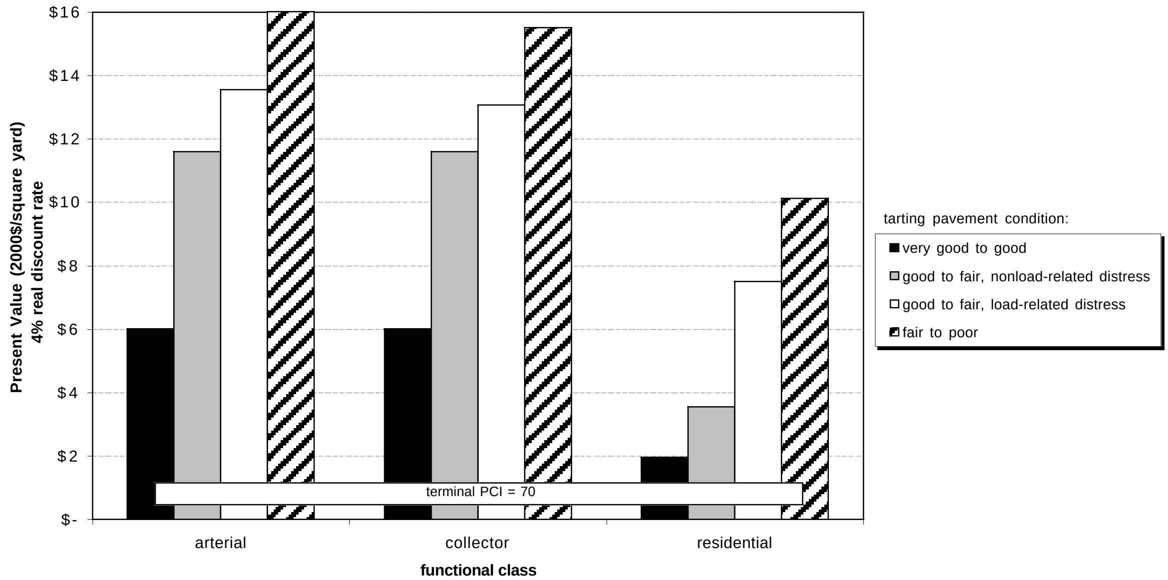

Figure 1. Total lifecycle costs ($/SY) of existing AC streets using terminal pavement condition index (PCI) of 70

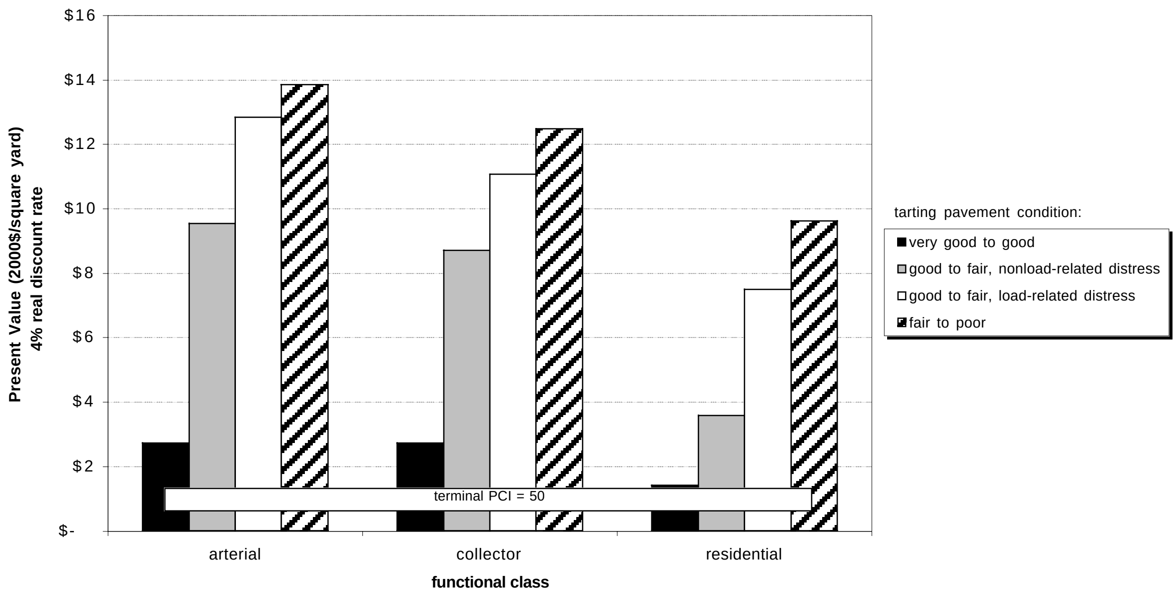

Figure 2. Total lifecycle costs ($/SY) of existing AC streets using terminal pavement condition index (PCI) of 50

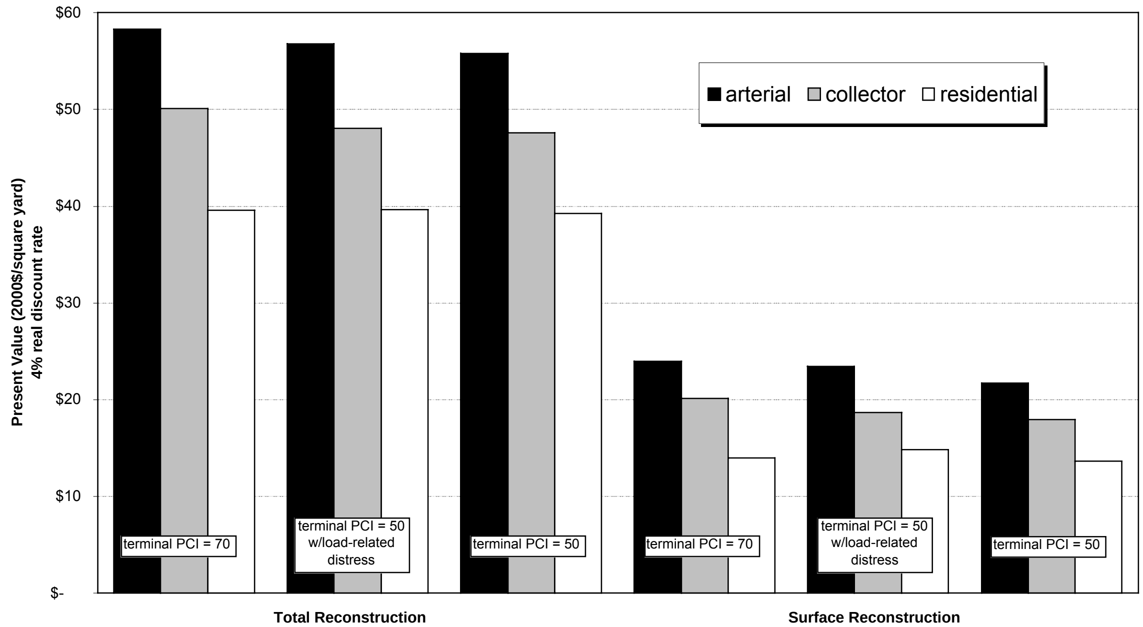

Figure 3. Total lifecycle costs ($/SY) of reconstructed AC streets using terminal pavement condition index (PCI) of 70, 50 w/load-related distress, and 50 w/nonload-related distress

Table 1. Lifecycle costs ($/SY) of conventional and high-albedo AC pavements, using lifecycle scenarios describing existing streets and load-related distress

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost	Delta Cost
Arterial Streets					
Conventional AC	$ 6.53	$ 6.07	$ 1.08	$ 11.50	
High-â AC (aggregate method), Δâ=0.1	$ 6.53	$ 3.48	$ 0.20	$ 9.81	$ (1.71)
High-â AC (aggregate method), Δâ=0.2	$ 6.53	$ 3.31	$ 0.54	$ 9.31	$ (2.22)
High-â AC (chipseal method), Δâ=0.1	$ 7.19	$ 3.25	$ 1.19	$ 9.25	$ (2.27)
High-â AC (chipseal method), Δâ=0.2	$ 7.19	$ 2.96	$ 1.58	$ 8.57	$ (2.95)
Collector Streets					
Conventional AC	$ 6.53	$ 3.71	$ 0.30	$ 9.94	
High-â AC (aggregate method), Δâ=0.1	$ 6.53	$ 2.62	$ 1.33	$ 7.82	$ (2.12)
High-â AC (aggregate method), Δâ=0.2	$ 6.53	$ 2.44	$ 1.41	$ 7.56	$ (2.38)
High-â AC (chipseal method), Δâ=0.1	$ 7.19	$ 2.43	$ 1.74	$ 7.89	$ (2.05)
High-â AC (chipseal method), Δâ=0.2	$ 7.19	$ 0.42	$ 0.06	$ 7.56	$ (2.38)
Residential Streets					
Conventional AC	$ 5.19	$ 1.55	$ -	$ 6.74	
High-â AC (aggregate method), Δâ=0.1	$ 5.19	$ 1.24	$ 0.35	$ 6.07	$ (0.67)
High-â AC (aggregate method), Δâ=0.2	$ 5.19	$ 1.16	$ 0.39	$ 5.96	$ (0.78)
High-â AC (chipseal method), Δâ=0.1	$ 5.85	$ 1.06	$ 0.51	$ 6.41	$ (0.33)
High-â AC (chipseal method), Δâ=0.2	$ 5.85	$ 0.46	$ 0.05	$ 6.26	$ (0.48)

Table 2. Lifecycle costs ($/SY) of conventional AC and ultra-thin whitetopping pavements, using lifecycle scenarios describing the rehabilitation of a severely distressed intersection

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost
Conventional AC	$ 9.61	$ 19.30	$ -	$ 28.90
UTW (4”)	$ 24.50	$ 3.39	$ -	$ 27.90

Table 3. Lifecycle costs ($/SY) of conventional AC, PCC, and high-albedo AC pavements, using lifecycle scenarios describing totally reconstructed streets and load-related distress

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost	Delta Cost
Arterial Streets					
Conventional AC	$ 49.60	$ 2.18	$ 0.76	$ 51.00	
Plain, Jointed PCC (6”)	$ 43.90	$ 9.30	$ 5.49	$ 47.70	
High-â AC (aggregate method), Δâ=0.1	$ 49.60	$ -	$ -	$ 49.60	$ (1.40)
High-â AC (aggregate method), Δâ=0.2	$ 49.60	$ -	$ 5.09	$ 44.50	$ (6.50)
High-â AC (chipping method), Δâ=0.1	$ 50.00	$ -	$ 5.13	$ 44.90	$ (6.10)
High-â AC (chipping method), Δâ=0.2	$ 50.00	$ -	$ 10.20	$ 39.80	$ (11.20)
Collector Streets					
Conventional AC	$ 42.20	$ 2.06	$ 1.13	$ 43.10	
Plain, Jointed PCC (5”)	$ 41.30	$ 4.22	$ 5.16	$ 40.40	
High-â AC (aggregate method), Δâ=0.1	$ 42.20	$ -	$ -	$ 42.20	$ (0.90)
High-â AC (aggregate method), Δâ=0.2	$ 42.20	$ -	$ 4.33	$ 37.90	$ (5.20)
High-â AC (chipping method), Δâ=0.1	$ 42.60	$ -	$ 4.37	$ 38.20	$ (4.90)
High-â AC (chipping method), Δâ=0.2	$ 42.60	$ -	$ 8.71	$ 33.90	$ (9.20)
Residential Streets					
Conventional AC	$ 34.80	$ 1.98	$ 1.18	$ 35.60	
Plain, Jointed PCC (4.5”)	$ 38.20	$ -	$ 4.77	$ 33.40	
High-â AC (aggregate method), Δâ=0.1	$ 34.80	$ -	$ 1.88	$ 32.90	$ (2.70)
High-â AC (aggregate method), Δâ=0.2	$ 34.80	$ -	$ 5.09	$ 29.70	$ (5.90)
High-â AC (chipping method), Δâ=0.1	$ 35.20	$ -	$ 5.15	$ 30.10	$ (5.50)
High-â AC (chipping method), Δâ=0.2	$ 35.20	$ -	$ 7.82	$ 27.40	$ (8.20)

Table 4. Lifecycle costs ($/SY) of conventional AC and high-albedo AC pavements, using lifecycle scenarios describing surface reconstructed streets and load-related distress

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost	Delta Cost
Arterial Streets					
Conventional AC	$ 18.20	$ 3.11	$ 0.12	$ 21.20	
High-â AC (aggregate method), Δâ=0.1	$ 18.20	$ 2.05	$ 1.11	$ 19.10	$ (2.10)
High-â AC (aggregate method), Δâ=0.2	$ 18.20	$ 1.88	$ 1.24	$ 18.80	$ (2.40)
High-â AC (chipping method), Δâ=0.1	$ 18.60	$ 1.76	$ 1.27	$ 19.10	$ (2.10)
High-â AC (chipping method), Δâ=0.2	$ 18.60	$ 0.37	$ 0.22	$ 18.70	$ (2.50)
Collector Streets					
Conventional AC	$ 14.80	$ 2.60	$ 0.65	$ 16.70	
High-â AC (aggregate method), Δâ=0.1	$ 14.80	$ 1.93	$ 1.31	$ 15.40	$ (1.30)
High-â AC (aggregate method), Δâ=0.2	$ 14.80	$ 0.45	$ -	$ 15.20	$ (1.50)
High-â AC (chipping method), Δâ=0.1	$ 15.20	$ 0.42	$ 0.06	$ 15.60	$ (1.10)
High-â AC (chipping method), Δâ=0.2	$ 15.20	$ 0.37	$ 0.26	$ 15.30	$ (1.40)
Residential Streets					
Conventional AC	$ 11.40	$ 2.60	$ 0.65	$ 13.30	
High-â AC (aggregate method), Δâ=0.1	$ 11.40	$ 1.93	$ 1.31	$ 12.00	$ (1.33)
High-â AC (aggregate method), Δâ=0.2	$ 11.40	$ 0.45	$ -	$ 11.80	$ (1.50)
High-â AC (chipping method), Δâ=0.1	$ 11.80	$ 0.42	$ 0.06	$ 12.20	$ (1.10)
High-â AC (chipping method), Δâ=0.2	$ 11.80	$ 0.37	$ 0.26	$ 11.90	$ (1.40)

Table 5. Lifecycle costs ($/SY) of conventional AC and ultra-thin whitetopping pavements, using lifecycle scenarios describing reconstructed streets

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost
Totally Reconstructed Streets				
Conventional AC, arterial	$ 49.60	$ -	$ 7.35	$ 42.20
Conventional AC, collector	$ 42.20	$ -	$ 7.03	$ 35.20
Conventional AC, residential	$ 34.80	$ -	$ 6.96	$ 27.80
Surface Reconstructed Streets				
Conventional AC, arterial	$ 18.20	$ 0.65	$ 0.39	$ 18.50
Conventional AC, collector	$ 14.80	$ 0.65	$ 0.47	$ 15.10
Conventional AC, residential	$ 11.40	$ 0.65	$ 0.47	$ 11.60
UTW (3”)	$ 20.90	$ 0.23	$ -	$ 21.10

Table 6. Lifecycle costs ($/SY) of conventional AC, PCC, porous, resin, and high-albedo AC pavements, using lifecycle scenarios describing new parking lots

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost
AC - high maintenance	$ 17.00	$ 14.00	$ -	$ 31.00
AC - best guess maintenance	$ 17.00	$ 7.89	$ -	$ 24.89
AC - low maintenance	$ 17.00	$ 7.78	$ -	$ 24.78
PCC - high maintenance	$ 17.70	$ 6.19	$ -	$ 23.90
PCC - best guess maintenance	$ 17.70	$ 5.08	$ -	$ 22.80
PCC - low maintenance	$ 17.70	$ 4.39	$ -	$ 22.10
Porous pavement - Invisible Structures, Inc.	$ 34.80	$ 6.22	$ -	$ 41.00
Porous pavement - Bartron Corp.	$ 42.50	$ 6.22	$ -	$ 48.70
Porous pavement - Presto Products Co.	$ 34.80	$ 6.22	$ -	$ 41.00
Resin pavement - Soil Stabilization Co.	$ 27.10	$ 5.03	$ -	$ 32.10
High-â AC (sealcoat method) - high, Δâ=0.1	$ 23.20	$ 15.20	$ -	$ 38.40
High-â AC (sealcoat method) - high, Δâ=0.2	$ 23.20	$ 13.00	$ -	$ 36.20
High-â AC (sealcoat method) - best guess, Δâ=0.1	$ 23.20	$ 12.50	$ -	$ 35.70
High-â AC (sealcoat method) - best guess, Δâ=0.2	$ 23.20	$ 12.10	$ -	$ 35.30
High-â AC (sealcoat method) - low, Δâ=0.1	$ 23.20	$ 11.20	$ -	$ 34.40
High-â AC (sealcoat method) - low, Δâ=0.2	$ 23.20	$ 11.20	$ -	$ 34.40

Table 7. Lifecycle costs ($/SY) of conventional AC and ultra-thin whitetopped pavements, using lifecycle scenarios describing reconstructed parking lots

Present Values using 4% real discount rate, expressed in 2000$	Initial Costs	Future Costs	Residual Value	Total Lifecycle Cost
Conventional AC - high	$ 23.60	$ 7.70	$ -	$ 31.30
Conventional AC - best guess	$ 23.60	$ 4.44	$ -	$ 28.00
Conventional AC - low	$ 23.60	$ 4.21	$ -	$ 27.80
UTW (4")	$ 15.90	$ 2.36	$ -	$ 18.30

Table 8. Summary of reflective pavement technology assessment

	Paving Technology	Applications				LCC	Tech Maturity	Pros	Cons	Market Barriers
		Arterial Streets	Collector Streets	Residential Streets	Parking Lots					
Technologies currently in use in U.S.	**Portland cement concrete**	X	X	X	X	LCC competitive with conventional AC reconstruction	Used extensively in several major cities; existing street installations up to 70 years old	Long service life; low maintenance requirements; high strength	High first cost	Agencies constrained by first costs; misplaced incentives for developers; future costs of repairing utility cuts can be prohibitive
	Whitetopping	X	X	X	X	LCC competitive with conventional AC reconstruction	Over 150 existing street installations up to 10 years old	Low maintenance; alternative to reconstructing distressed AC; performance of existing projects better than expected	High first cost; not suitable for high truck-volume streets	Lack of information; lack of contractors and competitive bidding
	High-albedo chip seals in conjunction with AC and ACOLs		X	X		If incremental costs low and durability benefits significant, LCC can be significantly lower than conventional AC	Common surface treatment on low-volume streets	Does not require changes in current maintenance methods; only that it be done in conjunction with all new/reconstructed AC and ACOLs using high-â chips	Incremental costs and availability of high-â chips unknown; low-volume streets only	Potential lack of proximity to sources of high-albedo aggregates
	Porous pavements				X	Current LCC higher than conventional AC	Used widely for parking lots & access lanes; many installations up to 15 years old	Long service life; low maintenance (watering/mowing); minimizes stormwater runoff; provides durable green space	High first cost; only suitable for low-volume parking lots and access lanes	Not suitable for high-volume applications
	High-albedo asphalt emulsion sealcoats				X	Current LCC higher than conventional AC	Established niche market for parking lots & private surfaces; existing installations up to 8 years old	Does not require changes in current construction/maintenance methods, only changes in selection of surface treatment	Expensive; existing high-â sealcoat emulsions are decorative; technology not yet optimized for reflectivity	"Black is better" culture
Technologies in development/not used in U.S.	**Resin pavements**				X	Current LCC higher than conventional AC	No existing street installations; few existing parking lot installations	Lab tests indicate strength equivalent to AC pavements	Existing installations mostly bikeways, walkways, access lanes; performance in streets and parking lots unknown	Lack of testing infrastructure and demonstration sites
	High-albedo aggregates in AC and ACOLs	X	X	X		If incremental costs low and durability benefits significant, LCC can be significantly lower than conventional AC	No existing installations	Does not require changes in current construction methods, only changes in selection of constituent aggregates	Incremental costs and availability of high-â aggregates unknown; lag time associated with realizing durability and reflectivity benefits	Potential lack of proximity to sources of high-albedo aggregates
	High-albedo "chipping" of AC and ACOLs	X	X	X		If incremental costs low and durability benefits significant, LCC can be significantly lower than conventional AC	No existing installations in U.S., common practice in Britain	Requires only small changes in current construction methods	Incremental costs and availability of high-â chips unknown; maintenance over long term unknown	Potential lack of proximity to sources of high-albedo aggregates Lack of US experience

ACOL = asphalt concrete overlay

â = albedo